Voltage Regulation for Energy Conservation: A Utility Case Study

Wei Sun[1], Qun Zhou[2], Evan Leebens, Kelly Nelson, Cole Sandness, Damber Chaudhary[3],
Electrical Engineering and Computer Science
South Dakota State University
Brookings, SD 57007
[1]wei.sun@sdstate.edu, [2]julie.zhou@sdstate.edu,
[3]damber.chaudhary@sdstate.edu

Ben Pierson[4], and Ted Smith[5]

Engineering and Operations
Sioux Valley Energy
Colman, SD 57017
[4]ben.pierson@siouxvalleyenergy.com,
[5]ted.smith@siouxvalleyenergy.com

Abstract **– As a critical function in distribution automation, voltage regulation enables the reduction of peak demand and contributes to energy conservation. This paper presents a utility case study of Sioux Valley Energy's voltage regulation strategy for energy conservation. The strategy involves software modeling, voltage setting recommendation and implementation, result analysis, and cost benefit analysis. The utility applies this strategy in its distribution network. Three different substations are considered to represent various load profiles of the rural, the urban, and the mixed areas. Typical winter, summer, spring, and fall loads are used and compared in this case study. The analysis and implementation results demonstrate the benefit of energy conservation from voltage regulation. Utilities could achieve long-term cost reductions and energy savings.**

Index Terms **–Energy conservation, load tap, voltage regulation**

I. INTRODUCTION

The load current across a distribution line varies throughout the day as the electricity demand varies. Therefore, power companies need to regulate and maintain customer voltages within an acceptable range described by the ANSI C84.1-2011 Standard [1]. As a critical function in distribution automation, voltage regulation is accomplished with precise control of line capacitor banks, line voltage regulators and substation transformer tap changers [2].

Voltage regulation not only maintains permissible customer voltages, but also contributes to energy conservation by reducing peak demand. Utilities used to operate at the high end of the permitted voltage range (114-126V) to ensure system reliability [3]. Thanks to emerging smart meters, utilities are able to reduce voltages even more and achieve higher energy savings.

According to the 2007 Next Generation Energy Initiative, the state of Minnesota requires energy saving to be 1.5% of annual retail energy sales for each utility [4]. Sioux Valley Energy (SVE) is a member-owned electric cooperative in east-central South Dakota and southwestern Minnesota that provides electrical services for more than 22,000 homes, farms, and businesses. If SVE could reduce its electrical demand through voltage regulation, not only would the results contribute to the state requirement of 1.5% energy savings, but also the cooperative and its members would see a direct benefit through cost reductions.

Sioux Valley Energy currently utilizes load tap changers to adjust voltages. A load tap changer is a voltage regulator located inside a substation and can be manually adjusted to scale the voltage. Figure 1 shows a picture taken at a SVE substation of the voltage regulator currently being used.

Figure 1. Sioux Valley Energy Voltage Regulator

A holistic voltage regulation strategy is proposed to SVE. First, substations with different load conditions are analyzed using Milsoft WindMil modeling software [5]. Then, voltage regulator settings are recommended and manually implemented by the SVE staff. The results of each voltage reduction are recorded for selected meters every fifteen minutes. These results are used for the next setting recommendation. These reductions are made until the threshold of 118V at the end user is reached. The yearly

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savings for each substation is calculated based on the various load types for winter, summer, spring, and fall. Finally, cost benefit analysis is conducted for long-term planning.

Sioux Valley Energy has applied this strategy in its distribution system, and the results demonstrate that voltage regulation is promising to achieve the energy conservation goal.

II. SVE Voltage Regulation Strategy

The holistic voltage regulation strategy to reduce the electric demand is shown in Fig. 2. This is an iterative procedure involving software modeling, voltage setting recommendation and implementation, result analysis, and cost benefit analysis. Each step is analyzed in the following.

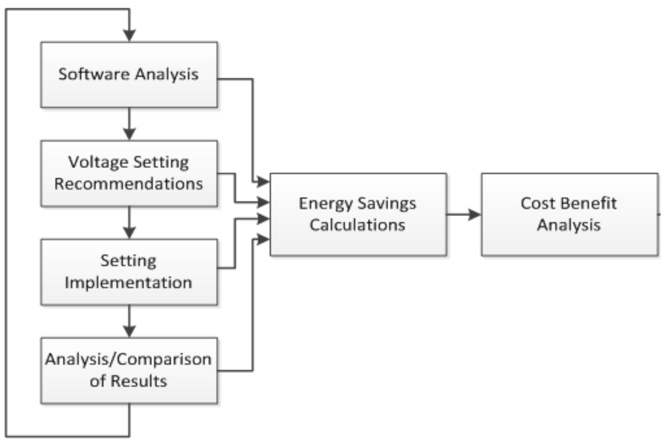

Figure 2. Block diagram of voltage regulation technique

A. Software Analysis

The software analysis step includes the initial and iterative analysis of each substation in order to recommend the voltage regulator settings.

1) First, use the Milsoft model provided for each substation to identify trouble meters, e.g., the first meters that dropped below the threshold voltage of 118 V. The voltage drop analysis is used to decrease the voltage at the regulator and determine the trouble meters.

2) Second, look at the weather for the upcoming days and acquire the peak loading data from a similar day. This data could then be used with the Milsoft model to simulate the voltage reduction recommended for that day. As the voltage reductions on the regulators increased, the weather played a bigger role. During days of warmer weather, the voltage could be reduced more than those when the weather was cold.

3) Finally, after receiving all the data from the voltage reductions, compare the Milsoft Windmil with the actual results. This is to determine how accurate the software represents the actual distribution network.

B. Voltage Setting Recommendations

Voltage reductions are recommended based on the software analysis. The recommendations is sent to the utility a day or two prior to the requested implementation day. The settings were then passed on from the utility engineer to the linemen. Some settings are recommended more than once to see how the loads varied with based on weather from day to day. The settings are also recommended in chronological order starting with a small voltage reduction of 0.5 volts before reaching the peak reduction between 1.5 and 3 volts.

C. Setting Implementation

The utility's linemen are responsible to make the changes suggested by the engineers on the specific day. At the end of the day, the regulators will be raised back to the original voltage. The settings recommended did not always match the setting implemented.

D. Analysis/Comparison of Results

The results of the voltage reductions are received from utility's smart metering system. The smart meters are located on each home and were set up by utility to automatically record the voltage, phase, meter number, and time, along with other information unnecessary for the project in 15 minute intervals for the entire voltage reduction period. The results received from utility will be checked to ensure that the user voltage did not drop below the threshold of 118 volts. This process continued until the threshold voltage was reached.

E. Energy Saving Calculations

After obtaining the maximum possible reductions on each substation, the energy saving calculations will be performed in this step. First, the load mix will be determined for each system. Among 3 basic load types in industry, constant power loads are unable to save any energy, while the constant impedance and constant current loads can. Then, the peak loads for summer and winder in each substation will be identified. Finally, the following equations are used to compute the total energy saving.

$$R_{Constant} = \frac{{V_{base}}^2}{P_{Peak}} \tag{1}$$

$$I_{New} = \frac{V_{base} - V_{Reduction}}{R_{Constant}} \tag{2}$$

$$P_{New} = (V_{base} - V_{Reduction}) \cdot I_{New} \cdot Load\ Mix\ Percent \tag{3}$$

$$P_{Saved} = P_{Peak} - P_{New} \tag{4}$$

These equations were calculated on each of the substations and during each season. For each season, the calculated saving was given per month. The values for each month were then multiplied by the number of months assumed in that season as shown above. The total kW saved was then multiplied by the price that the utility pays per kW.

F. Cost Benefit Analysis

The cost benefit analysis will compare the calculated energy savings with the costs that the utility would have to implement an automated voltage regulation system. The amount of time it would take for the utility to pay off this initial investment and begin seeing profits will also be calculated.

III. Case Study

The proposed strategy is tested in one portion of distribution network of SVE. Three different substations are considered to represent various load profiles of the rural, the urban, and the mix. Typical winter, summer, spring, and fall loads are used and compared in this study.

A. *Software Analysis Results*

The software analysis is performed in Milsoft WindMil for each of the three substations. The voltage drop analysis was used to determine which meters were the first to drop below the threshold voltage of 118 V. In SVE's model, every house has a meter with a distinct meter number. Approximately five to ten meters were chosen for each feeder line with at least two from each phase. Depending on the size of the substation, a total of 30-50 meters are chosen and given to SVE to monitor during the voltage reductions. Figure 3 shows a screenshot taken from WindMil demonstrating the voltage drop analysis with meters below 118 V highlighted with information boxes showing the specified voltage.

The software analysis was an iterative process performed before each new voltage setting recommendation was made. After all of the reductions were made, the Milsoft WindMil model was proved to be accurate according to the following procedure.

- Step 1: Obtain measured data from Prism Portal View on the day a regulator was lowered, including, substation load (kW) in 30 min intervals, and three phase current (A) in 30 min intervals
- Step 2: Average currents obtained from Portal View
- Step 3: Change load mix in Milsoft to match SVE assumptions; Lower substation regulator setting to match voltage reduction performed; Grow load on Milsoft to match average measured current from Portal View (to within 1's decimal place)
- Step 4: Run simulation in Milsoft; Obtain predicted load data, and compare results to actual measured load data

Table 1 shows the error analysis between the measured load and the predicted load from Milsoft WindMil for each of the three substations. As shown in the table the percent error was between 1.31% and 3.27%.

B. *Voltage Setting Recommendations Results*

The weather was a major concern when making voltage reduction recommendations. The recommendations made by the engineers were all able to be implemented on the actual day requested. All requests were to reduce the voltage by a certain amount from 8 am to 4 pm. This actual time varied slightly due to the schedule of the SVE lineman, but enough data was still obtained to get accurate results. Throughout the winter months specific days were chosen based on the weather conditions. Days of warmer weather were favorable for lowering the voltages. Table II shows a list of 19 recommended settings.

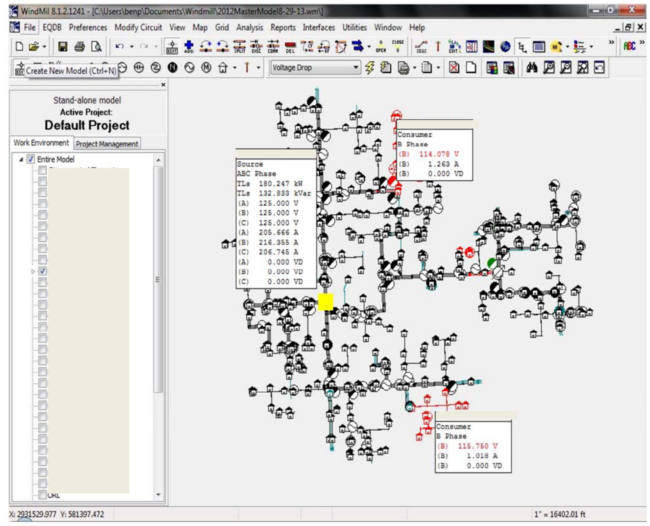

Figure 3. Milsoft Windmil Screenshot

TABLE I. Milsoft WindMil Model Error Analysis

Substation	Minimum Percent Error	Maximum Percent Error	Average Percent Error
1-rural	0.04%	4.71%	1.31%
2-urban	0.07%	4.17%	2.33%
3-mix	0.49%	5.01%	3.27%

TABLE II. The List of Recommended Voltage Reductions

Recommended Voltage Reductions					
Date	*Volt. Reduced*	*Subst ation*	*Date*	*Volt. Reduced*	*Substat ion*
11/22/2013	0.5	1	1/24/2014	1.5	2
11/27/2013	0.5	1	2/3/2014	2	3
11/27/2013	0.5	3	2/3/2014	2.5	2
11/27/2013	0.5	2	2/7/2014	1.5	1
12/5/2013	1	1	2/7/2014	2.5	3
1/21/2014	1	1	2/19/2014	1.5	1
1/21/2014	1	3	2/19/2014	3	3
1/21/2014	1	2	2/19/2014	2.5	2
1/24/2014	1	1	3/27/2014	3	2
1/24/2014	1.5	3			

C. *Setting Implementation Results*

During the January 21st and January 24th setting implementations at substation 1, an error occurred during the voltage reductions. As a result, one of the phases on the line was set 1 volt higher than the other two phases. This mistake was found by SVE and the data was not included in any calculations thereafter. On January 21st, substation 2 regulators were reduced by 2 volts due to a miscommunication with the lineman. The data was kept and substation 2 regulators were eventually dropped by 1 and 1.5 volts so that all data was available for future reference. These errors are noted in the table by an asterisk (*). Table III shows a list of the settings that were implemented. The maximum voltage reductions obtained are listed as bolded.

TABLE III. THE LIST OF ACTUAL VOLTAGE REDUCTIONS

Actual Voltage Reductions					
Date	***Volt. Reduced***	***Substation***	***Date***	***Volt. Reduced***	***Substation***
11/22/2013	0.5	1	1/24/2014	1.5	2
11/27/2013	0.5	1	2/3/2014	2	3
11/27/2013	0.5	3	2/3/2014	2.5	2
11/27/2013	0.5	2	2/7/2014	1.5	1
12/5/2013	1	1	2/7/2014	2.5	3
1/21/2014	2*	1	2/19/2014	**1.5**	**1**
1/21/2014	1	3	2/19/2014	**3**	**3**
1/21/2014	2*	2	2/19/2014	2.5	2
1/24/2014	2*	1	3/27/2014	**3**	**2**
1/24/2014	1.5	3			

D. *Analysis/Comparison of Results*

Table IV shows a summary of the date, voltage reductions, substations, and the results for each day. 1 meter reading dropped below 118 Volts means that for one 15 minute interval the user voltage showed less than 118 Volts. The total number of meter readings per day varied from one substation to another but was around 1000 readings. The lowest end user voltage ever reached was 115.5 volts one time. The majority of the readings below 118 were between 117 and 117.5 volts.

TABLE IV. METER SUMMARY OF VOLTAGE REDUCTION RESULTS

Voltage Reductions			
Date	***Voltage Reduced***	***Substation***	***Results***
11/22/2013	0.5	1	No meters below 118 V
11/27/2013	0.5	1	No meters below 118 V
11/27/2013	0.5	3	No meters below 118 V
11/27/2013	0.5	2	No meters below 118 V
12/5/2013	1	1	1 meter reading below 118 V
1/21/2014	1	1	Bad data
1/21/2014	1	3	No meters below 118 V
1/21/2014	2	2	No meters below 118 V
1/24/2014	1.5	1	Bad data
1/24/2014	1.5	3	No meters below 118 V
1/24/2014	1.5	2	No meters below 118 V
2/3/2014	2	3	3 meter readings below 118 V
2/3/2014	2.5	2	No meters below 118 V
2/7/2014	1.5	1	30 meter readings below 118 V
2/7/2014	2.5	3	6 meter readings below 118 V
2/19/2014	1.5	1	1 meter reading below 118 V
2/19/2014	3	3	7 meter readings below 118 V
2/19/2014	2.5	2	No meters dropped below 118 V
3/27/2014	3	2	No meters dropped below 118 V

E. *Energy Saving Calculations Results*

In this project, there are few constant current loads in SVE system. Therefore, only constant power and constant impedance loads are considered. It is assumed that each substation has the same load mix varied depending on the season. Table V shows the load mix according to the season. Table VI shows the assumptions for percent of peak power to use for each season.

TABLE V. LOAD MIX ASSUMPTIONS FOR EACH SEASON

Winter Loads (Nov. - Mar)	**Summer Loads (June - Aug)**	**Spring Loads(April-May)**	**Fall Loads (Sept. – Oct.)**
70% Constant Resistance	30% Constant Resistance	60% Constant Resistance	60% Constant Resistance
30% Constant Power	70% Constant Power	40% Constant Power	40% Constant Power

TABLE VI. PEAK PERCENTAGE PER SEASON

Substation	**Spring**	**Summer**	**Fall**	**Winter**
1	80%	94%	74%	85%
2	77%	96%	65%	89%
3	64%	89%	86%	90%

Considering maximum voltage reduction might not be achieved for all the time, the conservative voltage reductions are used in the calculation: 1 volt for substation 1, 2.5 volts for substation 2, and 1.5 volts for substation 3. Table VII shows the calculated savings for each substation. It can be seen that the substation 2 was able to save the most amount of money. This was because this substation had a large peak value for all seasons and had the ability for the greatest voltage reduction of all three substations. On the other hand, substation 1 had a much smaller load and was reduced by the least amount of voltage. The results will be used to project a total savings across the entire SVE network based on the assumption that there are 22 substations similar to substation 1, 7 similar to substation 2, and 6 similar to substation 3. One assumption was to not include a few SVE substations that only feed ethanol plants or data centers due to the lack of the ability to lower the voltage any further. This results in a total savings of $300,642.46.

TABLE VII. CALCULATED SAVINGS FOR EACH SUBSTATION

Substation	**Voltage Reduction Used**	**Winter Savings ($)**	**Fall Savings ($)**	**Summer Savings ($)**	**Spring Savings ($)**	**Total ($)**
1	1	$3,584.67	$641.99	$667.26	$454.31	$5,348.23
2	2.5	$8,978.12	$1,348.88	$2,934.09	$2,934.09	$15,143.79
3	1.5	$7,696.35	$1,512.88	$2,297.94	$1,321.96	$12,829.13

F. *Cost Benefit Analysis Results*

The cost benefit analysis was based on the energy savings calculations but also included the lost kWh sales not sold by SVE. The kWh sales were based on two cases. Case 1 looked at voltage regulation as a peak shaving method where SVE would run the reductions for 10-12 hours during the peak demand each month. Case 2 looked at using a fully automated voltage regulation system that would run 720 hours per month. Table VIII shows the results from Case 1 while Table IX shows the results from Case 2.

TABLE VIII. ENERGY SAVINGS CALCULATIONS WITH CASE 1

Substation	Voltage Reduction Used	Winter Savings ($)	Fall Savings ($)	Summer Savings ($)	Spring Savings ($)	Total ($)
1	1	$3,477.40	$622.78	$647.30	$440.71	$5,188.18
2	2.5	$8,729.32	$1,311.50	$2,852.78	$1,830.53	$14,724.13
3	1.5	$7,361.25	$1,447.01	$2,197.89	$1,264.41	$12,270.56

TABLE IX. ENERGY SAVINGS CALCULATIONS WITH CASE 2

Substation	Voltage Reduction Used	Winter Savings ($)	Fall Savings ($)	Summer Savings ($)	Spring Savings ($)	Total ($)
1	1	-$2,851.88	-$510.75	-$530.86	-$361.44	-$4,254.93
2	2.5	-$5,949.71	-$893.89	-$1,944.39	-$1,247.65	-$10,035.64
3	1.5	-$12,409.23	-$2,439.30	-$3,705.10	-$2,131.47	-$20,685.11

The total saving is projected across the entire network by assuming a certain number of substations similar to three in above tables. Table X shows a summary of the base case where no lost kWh was included compared to Case 1 and Case 2. Case 1 would be most beneficial to SVE as it would save them around $290,000/ year. Although Case 2 shows a total savings around -$288,000/ year, it would be most beneficial to SVE's customers. Case 2 would decrease SVE's customer's bills by minimizing unused kWh. SVE is a cooperative and makes decisions based on what is best for their members.

TABLE X. ENERGY SAVINGS SUMMARY

Substation	Dollar Savings/year
Projected Savings without kWh losses	$300,642.46
Case 1: 12 hours/month	$290,832.27
Case 2: 720 hours/month	-$287,968.49

The estimated cost of the software needed to fully automate the SVE system is $300,000. Another $200,000-$300,000 would be necessary to upgrade the system at the substation level. With a total cost of around $500,000-$600,000, it would take SVE 1.5-2.5 years to recover the costs based on Case 1. Case 2, while beneficial to SVE's customers would likely not be able to regain the initial cost.

G. Development of Voltage Regulation Strategy Results

The final strategy was sent to SVE and included the results from the software analysis and voltage reductions, energy savings calculations, and cost benefit analysis. Using the results from this project, SVE will use the strategy to determine if the cost of the overall system upgrade is economically beneficial. They will be able to consider both cases presented and make a decision. The strategy can also be used by other cooperatives researching whether the upgrade would be feasible on their own system.

IV. CONCLUSIONS

This paper presents a utility case study of Sioux Valley Energy's voltage regulation strategy for energy conservation. The holistic strategy involves software modeling, field implementation, and cost benefit analysis. The utility applies this strategy in its distribution network. The analysis and implementation results demonstrate the benefit of energy conservation from voltage regulation. It is also important to consider kWh losses from energy conservation. If the voltage regulation is implemented in a certain time (like 12 hours per month), there are still significant savings. The duration of applying voltage regulation depends on utilities' operation goals, and can be determined by using cost benefit analysis described in this paper. The generic procedure and results from this paper can also be used for power utilities to design and implement the tailored voltage regulation strategy for their own systems.

REFERENCES

[1] American National Standard. For Electric Power Systems and Equipment – Voltage Ratings (60 Hertz). ANSI C84.1-2011.

[2] ABB. Volt-VAr Management. Available: http://www.abb.com/product/db0003db004279/8a9ccd0beb3d3097c1257af700239f9a.aspx.

[3] Kellogg Warner and Ron Willoughby, "Conservation voltage regulation: an energy efficiency resource," *IEEE Smart Grid Newsletter*, Apr. 2013.

[4] State Energy Office. Minnesota Department of Commerce. "Minnesota next generation's energy initiative". Available: http://mn.gov/commerce/energy/images/SummaryNext%20Generation%20Energy%20Initiative.pdf.

[5] Milsoft Engineering Analysis (EA) - WindMil®. Available: http://www.milsoft.com/utility-solutions/upgrades/milsoft-engineering-analysis-ea-windmil%C2%AE.